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Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality—A methodology to support discussions on land-use perspectives

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Abstract

Intensively managed agricultural areas in North-Western Europe have been undergoing a shift from solely production oriented use to provision of multiple services and functions. Design and assessment of multifunctional agricultural landscapes could be supported by exploration of trade-offs between financial returns from agriculture, landscape quality, nature conservation and environmental quality. This paper presents the Landscape IMAGES methodology for spatially explicit exploration of options for multifunctional agriculture in landscapes at a scale of a few km^2. The framework has been developed to support discussions and inform decision making by local and regional policy makers, land owners and land managers. Other relevant stakeholders could include non-governmental organizations representing nature conservation and environmental protection objectives.

The structure of the Landscape IMAGES framework prototype is elaborated and its functioning is illustrated with a near-real example of a grassland-dominated landscape with hedgerows bordering the fields. In this landscape, four objectives are being pursued by adjusting land-use intensity and hedgerow presence: (1) acceptable agronomic yields for farms, (2) diversification of the botanical composition of fields and hedgerows, (3) variation in plant communities in the fields and half-openness of the landscape, and (4) reduction of nutrient losses to the environment. For exploration of the trade-offs between multiple objectives a heuristic search method (i.e., differential evolution) is employed, which yields a large range of alternative, acceptable configurations of the landscape. The framework provides explicit insight in the trade-off between the objectives and is implemented in a visual application that enables the comparison of alternative options. The method can be applied to a range of spatially explicit land-use and nature allocation problems and will further evolve as a result of anticipated interactions with stakeholders.

Keywords: Multifunctional agriculture; Discussion support; Learning; Optimization; Nature conservation; Landscape; Scales

1. Introduction

1.1. Context and rationale

Over the last two decades, attention in policy, land-use planning and research directed at intensively managed agricultural areas in North-Western Europe has shifted from production to provision of multiple services and functions by agriculture (Vos and Meekes, 1999). Such multifunctional land-use issues are for example maintenance or improvement of landscape structure, sustainable management of renewable natural resources, preservation of biodiversity and contribution to socio-economic viability of rural areas (OECD, 2001). A normative interpretation of multifunctional agriculture (MFA) was adopted by the European Union and used in its Agenda 2000 agricultural reform, by

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recognizing and encouraging the range of services provided by farmers and advocating a multi-sectoral and integrated approach to the rural economy. In a number of European countries the notion of MFA has become embedded in legislation, in others it is used in relation with notions such as sustainable development and rural development (Kröger and Knickel, 2005).

The increased attention for MFA can be attributed to a combination of many sometimes interacting factors, of which sufficient or even surplus production capacity, increased environmental awareness and other new societal demands such as the need for recreational area are the most pronounced. Due to the changes in land-use objectives for the involved stakeholders, the decision making process concerning land-use at different scales has become to a large degree a spatial planning process, integrating issues of agricultural production and its side-effects (nutrient losses, deterioration of food webs) at field and farm scales, and nature conservation, environmental protection and landscape quality at the regional/catchment scale.

To achieve an integrated view on the required adjustments and innovation in landscapes and land-use systems where complex, uncertain and value-laden issues occur, systems approaches that integrate various issues, stakes of social actors, disciplines and scales are indispensable. This type of work is characterized by a multi-disciplinary approach to problem solving, involving both technical and social sciences, and a high degree of stakeholder participation (Gough et al., 1998; Bland, 1999). Potential stakeholders range from the actual land owners and land managers to local residents and citizens, the latter mostly represented by governmental and non-governmental organizations such as nature conservation and environmental protection groups. Also local and national policy makers have a strong stake.

The resulting complexity in both land-use planning issues and stakeholder interactions necessitates the use of supporting methodologies and models to inform stakeholders and policymakers, to design alternatives and to explore scenarios for the future. The role of model-based support systems should be sought in contributions to: (i) learning of stakeholders by providing a ‘learning laboratory’ wherein the learning cycle can be completed rapidly and the possibility of reflection on the results is offered (McCown, 2002) and (ii) widening the perspective or ‘frame’ of multiple stakeholders involved in discussions about natural resource management and planning on problems and their potential solutions (Sterk et al., 2005), so-called ‘reframing’ (Kaufman and Smith, 1999; Bouwen and Taillieu, 2004). The approach of ‘discussion support systems’ as proposed by Nelson et al. (2002) aims to contribute to learning and dialogue between stakeholders about development options (Hansen, 2005), by addressing issues of common interest, and explicit examination of the consequences of different objectives and preferences (Struif Bontkes and Van Keulen, 2003). Therefore, an integrated analysis of multifunctional agricultural land-use systems involves an assessment of various performance criteria of the systems. The exploration of development options involves the determination of the trade-offs between the performance criteria or objectives.

1.2. Related work

Existing spatially explicit, future-oriented land-use exploration approaches applied to agricultural landscapes dominated by cropping or grassland systems have focussed primarily on agroecological aspects of production, hydrology and nutrient loss abatement (O’Callaghan, 1995; Van Huylenbroeck, 1997; Seppelt and Voinov, 2002; Wang et al., 2004; Matthews et al., 2006). From the perspective of landscape ecology considerable attention has been paid to the analysis of species distribution in relation to agricultural landscape structure (e.g., Brooker, 2002) and effects of changes in landscape structure have been evaluated in scenario studies (e.g., Dolman et al., 2001; Münier et al., 2004; Prato, 2005). Approaches for combined optimization of agricultural land-use and landscape elements configuration to improve habitat quality and nature conservation value are scarce (Wossink et al., 1999; Van Langevelde et al., 2002; Groeneveld, 2004). In contrast, in agro-forestry a considerable body of experience with multi-criteria planning of forest management in relation to habitat suitability has been developed over the last years (e.g., Store and Kangas, 2001). Moreover, these approaches have been applied in a participatory manner with stakeholders (Kangas et al., 2005; Mendoza and Prabhu, 2005). A recent broad inventarisation of existing approaches, tools and frameworks for multifunctionality of agriculture in the European Union carried out in the MultAgri project commissioned by the EC revealed that (Kröger and Knickel, 2005):

- More holistic conceptual and analytical frameworks are required that address multifunctionality of agriculture.
- Integrative research tools and tool combinations are needed to better assess the wider effects of programmes aiming for improved multifunctionality of agriculture.
- More attention is necessary for education and training in inter- or trans-disciplinary work and the development and practical application of integrated assessment methods and tools.

1.3. Objectives

In this paper we present a spatially explicit, GIS-based land-use optimization methodology named Landscape IMAGES (Interactive Multi-goal Agricultural Landscape Generation and Evaluation System). This approach combines agronomic, economic and environmental indicators with biodiversity and landscape quality indicators. The

paper focuses on the method of combination of multiple objectives and their spatially explicit evaluation at different hierarchical levels, rather than the technical aspects of the heuristic trade-off exploration methodology. A near-real implementation of the prototype framework is applied to a case study area in the Netherlands, which is described in Section 2. The structure of the proposed framework and its specifications is introduced in Section 3. Results of explorations are presented and analysed in Section 4. In Section 5, the degree to which the developed methodology meets the demands for modelling frameworks supporting participatory approaches are discussed and some potential applications are described.

2. Case study

The region of the Northern Frisian Woodlands, The Netherlands (Fig. 1a), is characterized by a small scale landscape on predominantly sandy soils with dairy farming as the prevailing land-use activity. On some farms a limited proportion of up to 5% of the area is used for forage maize production, while the rest of the area is occupied by permanent grassland, rotationally grazed and mown. The fields with an average size of 2 ha are often surrounded by hedgerows. The average grazing season lasts 6 months from May to October. Grazing systems range from day and night grazing to restricted and zero grazing. The bio-physical farm and field characteristics and the societal demands as articulated in regulations to maintain landscape and land-use have limited the possibilities to convert to large scale agriculture in the past.

In the Northern Frisian Woodlands environmental cooperatives founded by farmers play an important role at regional level to realize a vital regional economy, attractive leisure and residence areas, a clean environment and maintenance of landscape and biodiversity (Renting and Van der Ploeg, 2001; Stuiver and Wiskerke, 2004; Anonymous, 2005). The initiatives of the environmental cooperatives are supported by local, regional and national governments, and farmers and landscape management organizations. The strengthening of landscape and nature values in combination with agricultural practice is being pursued by an array of measures, for instance (Anonymous, 2005):

- Application and improvement of nature conservation packages offered by national landscape management programmes for extensively used grasslands and for linear landscape elements such as hedgerows.
- Improvement of the ecological connectivity of the landscape by strategic allocation of linear landscape elements.
- Protection of meadow birds and adjustment of the grassland management patterns to encourage nesting and nest hatching.

The environmental cooperatives and other local stakeholders have solicited scientific support to evaluate proposed adjustments in the design and assessment of landscape and agricultural land-use practices. Various stakeholder groups have different questions:

- Farmers are interested in exploration of the opportunities for cost-efficient intensive farming in a landscape of small fields surrounded by hedgerows. One of the questions is to which extent parts of hedgerows can be removed without jeopardizing the typical character of the landscape. Another issue relates to possible contributions to nature, landscape and economic goals by differential management of fields close to and far from farm buildings.
- Farmers' environmental cooperatives are looking for insight in the additional value of their joint actions on the quality of the abiotic environment and the landscape.

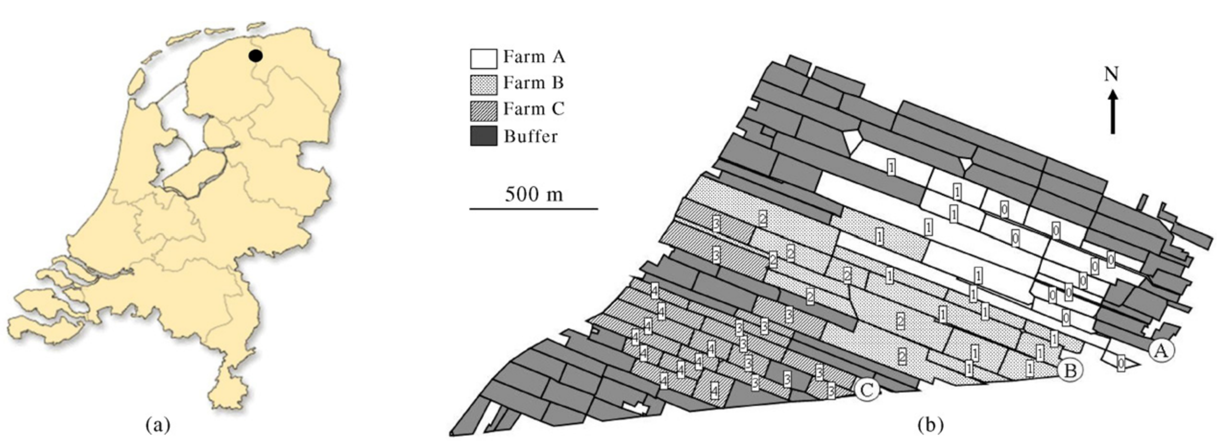

Fig. 1. (a) The position of the Northern Frisian woodlands (black dot) within The Netherlands. (b) Landscape of the case study area with fields for farms A–C and buffer fields. Numbers indicate the soil fertility level (0 = 140, 1 = 150, 2 = 160, 3 = 170, 4 = 180 kg N ha^{-1}). Circles with letters indicate the position of the farm houses and stables for the farms.

Table 1
Characteristics of the farms located in the case study area and included in the exploration

Characteristic	Farm A	Farm B	Farm C
Number of fields	16	16	21
Average area per field (ha)	2.62	2.93	1.70
Average distance of fields from farm yard (m)	690	703	650
Average soil fertility level[a]	0.63	1.55	3.41
Minimum proportion of grazed grass dry matter	0.40	0.25	0.35

[a] Relates to nitrogen delivery capacity of the soil, with the following levels: 0 = 140, 1 = 150, 2 = 160, 3 = 170, 4 = 180 kg N ha^{-1}.

- Landscape management organizations require insight in the effects of ‘good practices’ in hedgerow management on biodiversity and returns from farming.
- Policy developers at regional and national scale would benefit from information about the effectivity of investments into nature conservation.

The selected case study area of 232 ha enclosed by roads is presented in Fig. 1b. The majority of fields in this area belong to three farms, denoted A, B and C. Some relevant characteristics of the field configuration for each farm are listed in Table 1. A gradient in soil fertility was assumed in the case study area (Fig. 1b), related to the nitrogen delivery capacity by the soil. This gradient was hypothetical with the purpose to illustrate the capability of the framework to deal with spatial variations in bio-physical circumstances. The ranges in nitrogen delivery capacity by the soil used here are actually observed in the case study area.

3. Methodological framework of Landscape IMAGES

3.1. Conceptual model

The assessment of the performance of a given territory of any scale can be based on multiple criteria, such as economic returns, nature value, landscape identity and environmental quality indicators. When the occupation or use of the territory is heterogeneous, the area can be compartmented into discrete spatial units to arrive at land units with homogeneous activities. For a territory at landscape scale these activities on land units can for instance be the cultivation of a particular crop on a field or the presence of a hedgerow on a field border. The various activities make different contributions to the performance criteria and the activities of spatial units may interact with respect to the performance criteria. Consequently, different configurations of activities result in different values of the performance criteria, which can be positively correlated, but can also be conflicting. Insight into the relationships between the performance criteria in dependence of allocation of activities to land units offers input for choices considering the use of the territory. Interesting configurations of allocated activities are those that perform as good as possible when all the performance criteria are considered.

The exploration of the trade-offs between performance criteria or objectives can be formulated as a multi-objective design problem, which can be generally stated as follows:

$$\mathrm{Max}\,\mathbf{U}(\mathbf{x}) = (U_1(\mathbf{x}), U_2(\mathbf{x}), \ldots, U_k(\mathbf{x}))^{\mathrm{T}} \quad (1)$$

$$\mathbf{x} = (x_1, x_2, \ldots, x_n)^{\mathrm{T}} \quad (2)$$

Subject to i constraints:

$$g_i(\mathbf{x}) \leq h_i \quad (3)$$

where $U_1(\mathbf{x}), \ldots, U_n(\mathbf{x})$ are the objective functions that are simultaneously maximized or minimized, and $(x_1, \ldots, x_n)$ are the (integer) decision variables that represent the activities allocated to the n spatial units. The decision variables can take on a predescribed array of values, $\mathbf{x} \in S$, where S is the solution or parameter space. Constraints (Eq. (3)) can arise from the problem formulation, for instance by limitations on the inputs or outputs related to the activities.

The allocation of discrete activities to the spatial units makes the problem ‘NP hard’: no algorithm exists that guarantees that the exact k-dimensional trade-off surface is obtained under all circumstances, because the dimensionality of the problem, and therefore the computational difficulty, grows faster than any polynomial in the number of decision variables. Heuristic techniques such as genetic algorithms (GAs) and evolutionary strategies (ESs) can be employed to obtain approximations of the trade-off surfaces by a population of solutions, each representing a configuration of activities for the territory. GAs and ESs are adaptive search techniques based on the principles of natural evolution. Genetic operators for reproduction, selection, mutation and crossover (the latter only in GAs) are applied to a randomly generated population of solutions to improve its average performance criteria generation by generation (Bergey and Ragsdale, 2005). During this iterative process, solutions are selected for each new generation on the basis of Pareto optimality. A set of Pareto optimal solutions consists of solutions that are not dominated by other solutions, when all objectives $U_1(\mathbf{x}), \ldots, U_n(\mathbf{x})$ are considered. Using this concept the solutions can be ranked as follows (Goldberg, 1989):

1. The Pareto optimal sub-set is established.
2. This sub-set receives the highest rank and is removed from contention.
3. The procedure is repeated until all solutions have been ranked.

3.2. Production activities and agroecological relations

For the present case study the territory at landscape scale was compartmented into land units (Fig. 1b) representing

Table 2
Design criteria and the variants for each criterion as implemented for engineered grassland based dairy farming systems

Attribute	Design criterion	Number of variants
Production environment	Soil fertility	5 levels, 140, 150, 160, 170 and 180 kg N ha^{-1}
Production technique	Fertilizer application	11 levels of fertilizer application: 0, 25, 50, 75, 100, 125, 150, 200, 250, 300, 350 kg N ha^{-1}
	Harvesting regime	Valid combinations of 0–5 grazing periods, 0–5 mowing cuts and 3 dates of first harvest (before 1 June, 1–30 June, 1 July or later)

agricultural fields (polygons) and field borders (lines coinciding with polygon borders). Agricultural production activities were allocated to the fields, and field borders could be occupied by a hedgerow or remain unoccupied. An agroecological engineering approach was used to design *production activities*, which are defined as the cultivation of a crop or vegetation and/or management of a herd in a particular physical environment, completely specified by its inputs and outputs (Van Ittersum and Rabbinge, 1997). The inputs and outputs are fully determined by the physical environment, the plant and animal types and the applied production techniques. Therefore, the production activities were derived from factorial combination of *design criteria* (Hengsdijk and Van Ittersum, 2002) that explicitly characterize the physical environment (here: soil fertility), type of plants and animals (vegetation and herd) and production techniques (fertilizer application and harvesting regime). An overview of the design criteria and the variants per criterion is given in Table 2. Combinations of variants were filtered for agronomic feasibility. A total of 535 production activities were generated, between 98 and 114 per soil fertility level.

The inputs and outputs of the production activities were calculated from simplified empirical agroecological relations (Fig. 2). The relations between fertilizer N application rate and N uptake in grass (Fig. 2a) and between N uptake and dry matter yield (Fig. 2b) were derived from the results of cutting and grazing experiments (Snijders et al., 1987; Lantinga et al., 1999), using an expolinear equation (cf. Groot et al., 2003). The intercept in Fig. 2a represents the N available from delivery by the soil and was determined by the soil fertility level (see Table 2). Productive grassland area was corrected for the presence of hedgerows, which were assumed to have a width of 10 m. Compared to a harvesting regime of only mowing, the annual N uptake and dry matter yield under harvesting regimes that included grazing were reduced dependent on the number of grazing cuts, because of larger harvest losses and sward deterioration under grazing (Lantinga et al., 1999). Three periods for the first harvest were defined: before 1 June, between 1 June and 1 July, and after 1 July. The length of growth periods of the grass was calculated from the harvesting regime, i.e., the number of mowing and grazing cuts throughout the growing season and the date of first harvest.

From the dry matter yield and the length of growth periods for individual cuts the production of energy for lactation (1 kVEM = 6.9 MJ net energy for lactation; Van Es, 1978) was estimated. The associated milk production was calculated assuming an energy requirement of 0.85 kVEM per kg milk for cows producing 8000 kg milk per annum and a replacement rate of 25% according to Dutch feeding standards (Anonymous, 1997).

The relations between available nutrients and plant species diversity (Fig. 2c) are derived from experimentally obtained relationships between grassland productivity and species diversity (Bakker, 1989; Oomes, 1992), combined with the production curves in Fig. 2a and 2b. For borders

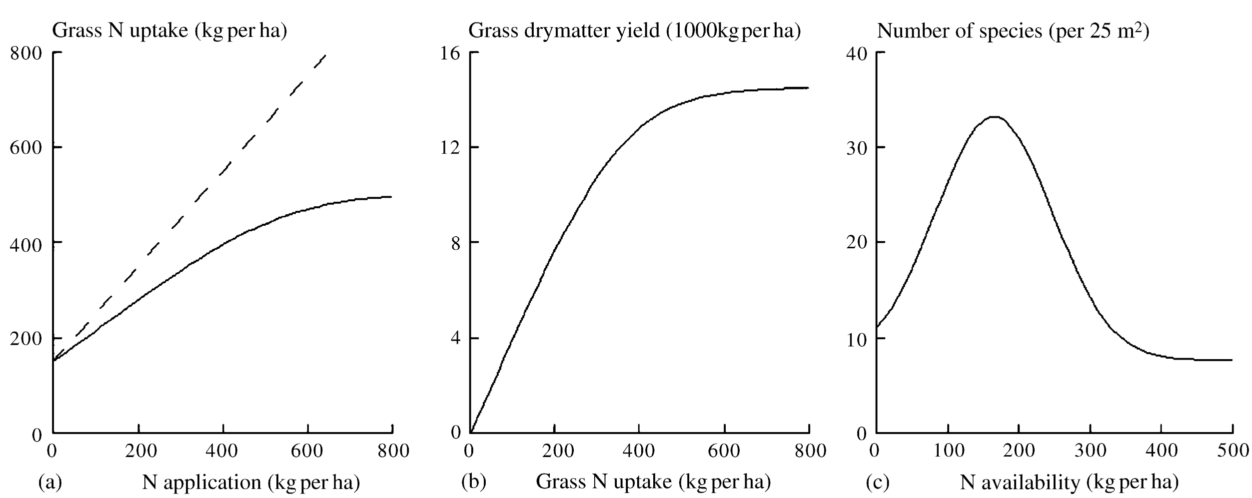

Fig. 2. Agroecological relations between (a) fertilizer N application and grass N uptake (solid line) and total N availability (dashed line), (b) N uptake and biomass production, and (c) total N availability and plant species number in grasslands.

occupied with hedgerows the same relation was used with the average nutrient availability of the adjacent fields as independent variable.

3.3. Production activity allocation problem

In the model agricultural production activities on the fields and hedgerows adjacent to the fields are allocated, taking into account spatial heterogeneity and spatial interactions. The model seeks to:

- maximize gross margin from agricultural production (U_P)
- minimize loss of nutrients to the environment (U_E)
- maximize nature value of fields and borders (U_N)
- maximize variation the landscape in terms of species presence and hedgerow allocation, i.e., half-openness (U_L)

subject to (see end of this section):

- limits to nutrient input
- proportion of herbage grazed

On the basis of the outputs of the production activities, the objective function values U_i were quantified as presented in Eqs. (4)–(7):

$$U_P = \sum_f (R_f + S_f - C_f) \tag{4}$$

where R_f is the returns from production for field f (€), S_f the subsidies for field f (€) and C_f is the variable costs for field f (€).

As indicator for the economic performance of farms gross margin was adopted (U_P; Eq. (4)), which is more sensitive to changes in farm management than total farm results, which also include fixed costs (Ondersteijn et al., 2003). The returns from production per field R_f were calculated directly from the milk production and the milk price (€0.35 per kg milk). Costs per field C_f were separated into costs related to production and transport costs. Costs for production were restricted to costs for harvesting by grazing or mowing and fertilizer costs. Transport costs associated with grazing and mowing management depended on the travel distance between farm yard and the field, the travel velocity and the frequency of visits to a field under particular management. The applicability of agri-environmental subsidies to individual fields was assessed on the basis of plant species abundance, and harvesting and fertilization regimes. The financial revenues from nature agri-environmental schemes (€254 or 1154 ha^{-1}) were added to the value of the objective function for economic results, U_P (Eq. (4)):

The species abundance in the grass swards and hedgerows (U_N) was used as an indicator for nature conservation value (Eq. (5)). For borders not occupied with hedgerows $S_b = 0$ was used. As a consequence, increases in both hedgerow length and species numbers in hedgerows resulted in an increase in U_N:

$$U_N = \frac{\sum_f (S_f A_f)}{\sum_f A_f} + 4\frac{\sum_b (S_b A_b)}{\sum_b A_b} \tag{5}$$

where S_f is the number of species on field f (ha^{-1}), A_f the area of field f (ha), S_b the number of species in border b (ha^{-1}) and A_b is the area of border b (ha).

Landscape quality (U_L) was equated to variation in the landscape (Eq. (6)). VAR($S_{f,i}$) was calculated as the variance of the species number for each field and its adjacent fields. This evaluation at field neighborhood level precluded high appreciation of landscapes with varying but clustered species numbers per field. VAR($S_{f,i}$) is a measure of the heterogeneity of the landscape in terms of the variation in colors and growth forms in grasslands (Stobbelaar et al., 2004). Hedgerows strongly influence the perception of landscapes by breaking up landscapes, providing diversity, perspective and pattern (Oreszczyn and Lane, 2000). In particular irregularity in the hedgerow pattern in landscapes is often highly appreciated. On the one hand hedgerows enclosing fields offer a sense of mystery and intimacy, while on the other hand the landscape should not be completely closed but offer overviews over the patchwork of fields (Oreszczyn and Lane, 2000; Weinstoerffer and Girardin, 2000). Therefore, the second term in Eq. (6) was included as a measure of half-openness of the landscape:

$$U_L = \sum_f \left(\mathrm{VAR}(S_{f,i}) + 10\left(0.5 - \mathrm{ABS}\left(\frac{\sum_{f,h} A_{f,h}}{\sum_{f,b} A_{f,b}} - 0.5\right)\right)^2 \right) \tag{6}$$

where VAR($S_{f,i}$) is the variance of species number on i fields adjacent to field f; $A_{f,h}$ the area of hedgerows around field f and $A_{f,b}$ is the area of borders with and without hedgerows around field f.

The loss of nutrients (U_E, Eq. (7)) was directly derived from the agroecological relations in Fig. 2a by calculating the difference between uptake and availability of N.

$$U_E = \sum_f E_f \tag{7}$$

where E_f is the nitrogen loss from field f (kg N).

The majority of fields in the case study landscape belong to farms A, B and C (Fig. 1b). The farm level represents an administrative level between landscape and fields, where the management decisions are taken. The values of the objective functions U_P, U_N, U_L and U_E were aggregated per farm and for the whole landscape of the case study area. In this paper, the results of the optimizations are evaluated after aggregation to the landscape scale, unless indicated otherwise. Fields in the landscape that are not used by

farms A, B or C were treated as buffer fields and were not included in the calculations of U_i. To these fields a random land-use activity was allocated during the initialization of the model, which was not modified during the optimization.

Farm level constraints were set for the average fertilizer application rate and the proportion of herbage that needs to be available for grazing. Maximum N application was fixed at 325 kg N ha^{-1} for all farms. This value was derived from the maximum allowed slurry N application of 250 kg N ha^{-1}, with an expected apparent recovery of 70%, and additional artificial fertilizer application of 150 kg N ha^{-1}. The minimum proportion of grazed herbage for each farm (Table 1) was calculated on the basis of the length of the grazing season (145 or 200 days) and the grazing system (day and night or only day grazing).

3.4. Pareto-based differential evolution

Exploration of the trade-offs between objectives was performed with a multi-objective implementation of the evolutionary strategy algorithm of differential evolution (DE) developed by Storn and Price (1995). Currently, DE is widely used in the research community due to its simplicity, efficiency and robustness (Bergey and Ragsdale, 2005; Mayer et al., 2005). DE involves the iterative improvement of a set of solutions or genotypes. Each allele in the genotype is a real number. In our application, the genotypes represented alternative landscapes, and the alleles were decision variables in which the land-use of an individual field and the occupation of the field borders were encoded. For each of the 53 fields belonging to the three farms in the case study landscape (Fig. 1b), two alleles were available to encode field use (x) and border occupation (z) separately, resulting in a total of 106 alleles per genotype. To this end the allele values were converted to discrete (Lampinen and Zelinka, 1999) or binary parameters.

A detailed description of the functioning of the algorithm is provided by Lampinen and Zelinka (1999) and Xue et al. (2003), and is summarized here. The algorithm was initialized by generating a set of solutions with random values for the x and z decision variables, only constrained by restrictions imposed on the parameter set: the possible production activities on fields for x, and the number of borders per field for z. This set was improved for a predefined number of generations. Criteria to evaluate the quality of the solutions were the Pareto ranking and within the same rank the crowdedness of the portion of the solution space where the solution was located, according to the crowding metric presented by Deb et al. (2002). Selection of solutions of better ranking results in a pressure normal to the trade-off region, whereas selection of solutions in less crowded parts of the solution space exerts a pressure tangential to the trade-off region, which promotes the spread over the solution space (Khor et al., 2005).

The following procedure for improvement of the solution set was applied:

1. Generation of a competitor for each individual solution in the set, by a combination of copying and recombination of alleles in a ratio that is governed by parameter CR.
2. Assessing the quality of the solutions and their competitors by ranking and calculation of the crowding metric.
3. Selection of either the original solution or its competitor for the new solution set.

To explore the extremes of the objective space, single-objective optimizations for the individual objectives were performed, also employing the DE algorithm. Here, the objective values of U_i were used as the selection criterion in step 3 (and step 2 was omitted).

The performance of the algorithm is affected by four (fixed) parameters. CR (value used in this study: 0.85) denotes the probability of mutation of an allele. F (0.15) controls the amplification of the mutations. MP (10) is the multiplication factor to calculate the population size from the number of alleles in each genotype, in this case 1060. G (12,000) is the number of generations and serves as the stopping criterion. The parameter values employed in this study were derived from factorial analysis in preliminary optimization runs.

Constraints are implemented as penalties to solutions that violate any of the constraints, so that these solutions will receive the lowest rank. These solutions are not selected for the next generation if a competitor has been composed that meets the constraints, and remain in the population otherwise.

3.5. Implementation

The model was implemented in the Microsoft .NET Development Environment. The landscape configuration data were directly accessed from ESRI shape files (Anonymous, 1998) with the ShapeLib.dll (URL: http://www.shapelib.maptools.org/). Software published on the Internet by K. Deb was used to perform the Pareto ranking and to calculate the crowding distance metric (URL: http://www.iitk.ac.in/kangal/soft.htm).

4. Results

The solution sets obtained after 12,000 generations of improvement by the DE algorithm covers a large range of possible configurations of the landscape in terms of land-use on fields and the placement of hedges on field borders. Replicated multi-objective optimization runs yielded similar extreme values for the four objectives (data not presented), although the distances between these extremes and those obtained by single-objective optimization were still considerable (Fig. 3). However, single-objective optimizations with constraints on other objectives indicated that the trade-

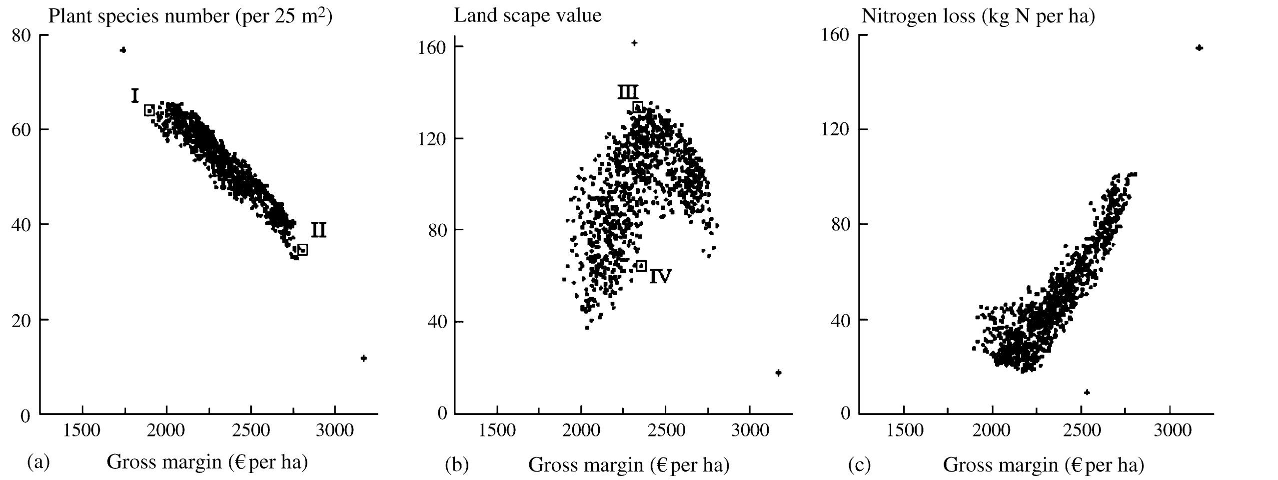

Fig. 3. Landscape scale trade-off curves between gross margin (€ per ha) and nature value (a), gross margin and landscape value (b) and gross margin and nitrogen losses (kg N ha^{-1}, c) after 12,000 generations of optimization (●). Four selected landscapes are indicated (□) and numbered I–IV. Extreme solutions obtained by single-objective optimization are indicated (+).

off frontier was closely approached in the multi-objective optimizations (data not presented). The results of an example solution set are presented here.

The trade-offs between the objectives at landscape scale are presented in Fig. 3, which shows the non-dominated Pareto optimal set for the four objectives, graphically represented in bi-plots. The gross margin ranged from ca. €1750 to 2750 ha^{-1}. These relatively high values for grasslands originated from the calculation of true milk production, estimated from net energy for lactation in grass, and not using merely a NEL-price. Moreover, some of the costs (veterinary, reproduction, and contractor) were not included in the calculations. Landscapes I and II in Fig. 3a represent extremes in the trade-off between gross margin and nature value, as found in the example solution set. The frequency distribution of species numbers in fields and nutrient loss per field for the selected landscapes show the large contrasts (Fig. 4). Landscape I (low gross margin, high nature value) is dominated by fields with production activities characterized by high species numbers (Fig. 4a) and low nutrient losses (Fig. 4b) as a consequence of low fertilizer inputs. Landscape II (high gross margin, low nature value) comprises more production activities where low species numbers occur (Fig. 4a). However, it also contains 14 low-input fields with production activities characterized by high species numbers where agri-environmental conservation packages apply, and thus subsidies are earned. In this landscape, production activities with a wide range of nutrient loss levels per field were allocated.

For each level of satisfaction of an objective, a large diversity of alternative solutions varying in other objectives was found. For example (Fig. 3b), at a certain level of gross margin larger variation in the landscape was achieved by improved spatial distribution of production activities varying in management intensities, in particular when intermediate or lower levels of gross margin would be

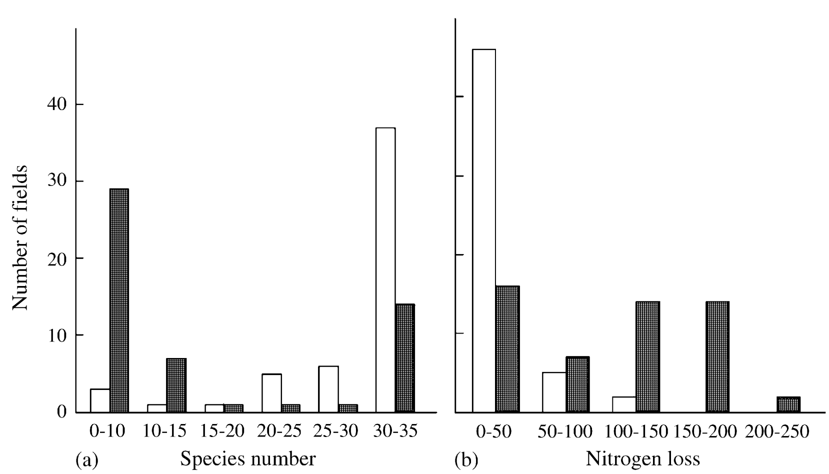

Fig. 4. Frequency distributions of plant species numbers (per 25 m^2; a) and nitrogen loss (kg N per ha; b) per field in optimized landscapes with high nature value (open bars; solution I in Fig. 3a), high gross margin (closed bars; solution II in Fig. 3a). Objective values for the solutions: I: U_P = €1898 ha^{-1}, U_N = 64.0 spp per 25 m^2, U_L = 58.7, U_E = 27.7 kg N ha^{-1}; II: 2806, 34.5, 81.9, 101.1.

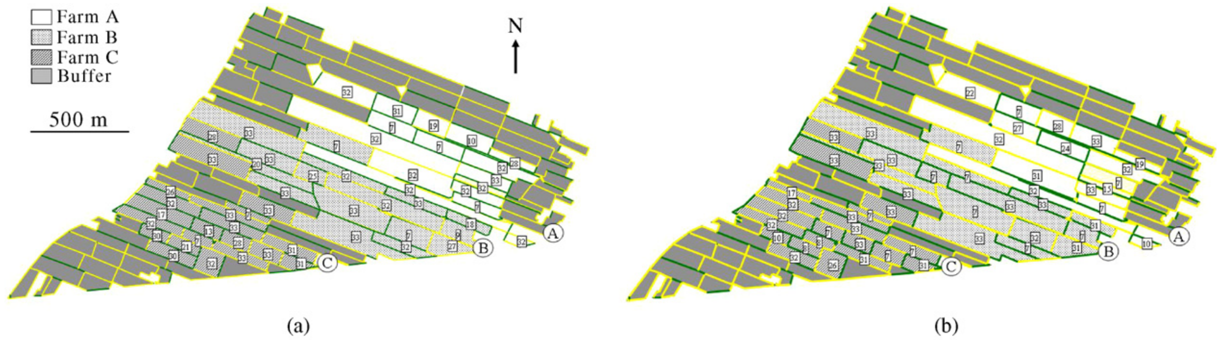

Fig. 5. Plant species numbers (per 25 m^2) per field and the presence of hedgerows (solid lines) in landscapes with high landscape value (a; solution III in Fig. 3b) or low landscape value (b; solution IV in Fig. 3b). Objective values for the solutions: III: U_P = €2334 ha^{-1}, U_N = 47.6 spp per 25 m^2, U_L = 133.6, U_E = 49.3 kg N ha^{-1}; IV: 2355, 53.4, 64.3, 32.5. Circles with letters indicate the position of the farm houses and stables for the farms.

acceptable. The larger variation in management intensity of production activities was illustrated by the spatial distribution of species abundance in fields, which reflects management intensity, and of hedge presence for selected landscapes III and IV (Fig. 3b) in Fig. 5. These landscapes had similar values for the other objectives.

The trade-offs between gross margin and nature value at different hierarchical levels are shown in Fig. 6. The data points in Fig. 6a represent the individual production activities which are defined at the field level. Combination of production activities at the farm level resulted in averaging out of extremes (Fig. 6b). As a result of the requirement of a minimum proportion of grazed herbage, the land-use was dominated by production activities with gross margins lower than €3000 ha^{-1}. These production activities were characterized by presence of grazing cuts, which have lower production efficiency than mowing cuts, due to lower net herbage production caused by trampling by cattle and larger herbage residues in the field after grazing. Differences in the ranges of objective values were observed between the farms (Fig. 6b). The larger range in the number of species in fields for farm B when compared to the other farms was caused by the lower required proportion of grazed herbage for this farm (see Table 1). The shift towards higher gross margin at the same nutrient availability/species number in fields for farms B and C when compared to farm A could be attributed to the higher soil fertility levels for farms B and C. These contrasts between the farms resulted in narrowing of the ranges in objective values at landscape scale (Fig. 6c), despite the fact that within the solution set species numbers in fields aggregated to farm level were highly correlated between farms. The correlation coefficients between farms determined for species numbers in fields over the whole solution set ranged between 0.75 and 0.85.

5. Discussion

The optimization study with the Landscape IMAGES framework demonstrated that trade-offs between multiple objectives can be effectively explored in a spatially explicit land-use allocation problem. The presented future-oriented explorations, employing principles of the agroecological engineering approach proposed by Hengsdijk and Van

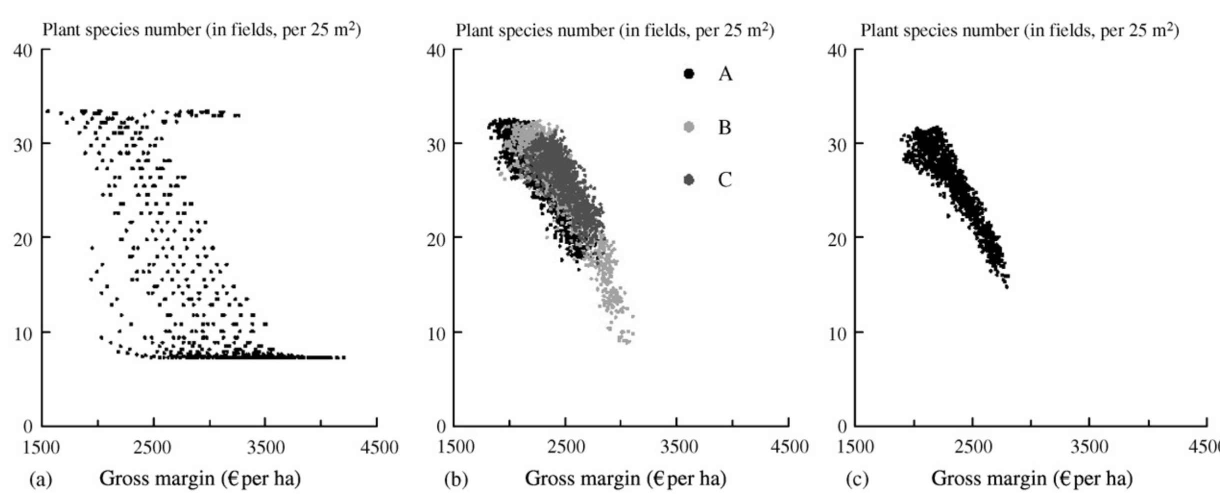

Fig. 6. Relationship between gross margin of agricultural practice (including subsidies for nature conservation) and the average, area-weighed abundance of species in fields for individual fields (a), farms (b) and the whole landscape (c).

Ittersum (2002), yield ex ante assessments of land-use alternatives to assist strategic decision making and to inform debates on landscape and land-use planning. The possibilities for multi-scale design and evaluation of landscapes offered by the framework, enabled evaluation of spatial interactions and their implications at higher hierarchical scales (Fig. 6). The solution sets contained a large range of possible configurations of the landscape in terms of land-use on fields and the placement of hedges on field borders. At a certain satisfaction level for an objective the potential 'window of opportunities' to improve on other objectives by selecting different production activities could be made explicit (Figs. 3–5).

The algorithm generated solutions that showed the trade-offs between four objectives across a wide range of objective values, although the extremes for individual objectives obtained in the single-objective optimization were not reached (Fig. 3). This phenomenon is more frequently encountered by heuristic methods to solve multi-objective optimization problems, due to insufficient selection pressure tangential to the trade-off region (Khor et al., 2005), and is apparently only partly alleviated by the applied crowding metric-based selection. Alternative solutions to this problem could involve enriching of the initial population for the multi-objective optimization with results from single-objective optimizations. This should be considered in future research.

The framework offers the opportunity to combine knowledge from diverse disciplines, so that trade-offs between objectives proposed by these disciplines can be evaluated. Thereby, assessment and enhancement of multi-functionality of land-use and landscape design could be supported. Currently, the prototype relationships implemented are still mainly focused on the 'natural' science approaches of agronomy, environment, ecology and landscape ecology, combined with the socio-cultural discipline of landscape science. The possibility to define objectives and apply constraints at the different hierarchical levels of field, farm and landscape provides the possibility for incorporation of sociological concepts such as farming styles, which can be characterized by variation in their predominant objectives and constraints in farming (Van der Ploeg, 1994). These styles have been shown to relate to the way farmers manage issues of sustainability and landscape maintenance (Busck, 2002; Schmitzberger et al., 2005). Incorporation of farming styles could be achieved by defining scenarios with contrasts in objectives and constraints at farm or landscape level, combined with developing a larger set of production activities with a larger array of production techniques and related input–output coefficients.

The generated alternatives offer ample opportunities for discussions with stakeholders on various topics. The current implementation with simplified agro-ecological relations illustrated that existing stakeholder questions can be addressed. For instance, the presented results showed differences between farms in ranges in the trade-off between gross margin and species abundance (Fig. 6b). This indicates that the potential room to manoeuvre can strongly depend on the bio-physical circumstances (soil fertility) and farm configuration (grazing system applied). In future versions with more elaborated agroecological relations, the determination of relationships between farm management practices, biodiversity and landscape identity can yield insight into the possibilities of increasing farming intensity on individual farms. By relating field and farm levels to landscape level when assessing nutrient losses and biodiversity, the added value of concerted action of farmers within environmental cooperatives can be quantified. Moreover, including hedgerow quality in the analysis will provide input for landscape management organizations to determine priorities in their management and extension programs.

The current version of the framework exhibits a number of requirements for effective model utilization in discussion support by, e.g., parameter, objective and constraint adjustment at the three relevant scales, and selection of dimensions for visualization to enable interrogation of the results. These features enable the assessment of issues of mutual interest and explicit examination of different objectives and preferences (cf. Struif Bontkes and Van Keulen, 2003). Moreover, the framework offers ample flexibility to adjust model functioning in consultation with stakeholders. Additional methods to effectively select alternatives that match the viewpoints of the respective stakeholders would further support stakeholder discussions. Some approaches are available and will be considered in our future work, for instance efficiency assessment of solutions by data envelopment analysis (Charnes et al., 1978), compromise analysis (Van Huylenbroeck, 1997) or preference ranking on the basis of the priority assigned to the objectives (Fonseca and Fleming, 1998; Anderson et al., 2005).

In future applications, the presented Landscape IMAGES framework could be applied to a range of spatially explicit land-use and nature allocation problems. Some possible issues are listed below:

1. Support of policy development on feasibility of new institutional arrangements for self-regulation, such as territorial contracts, wherein groups of land-users at the regional scale cooperate and conform to regulations to meet environmental and nature conservation aims (Wiskerke et al., 2003). This requires evaluation of repercussions of management practices of individual land-users at the regional scale.
2. Design of nature conservation strategies focusing on the relation between landscape structure and biodiversity. For example, mosaic management of grasslands at landscape or regional level could offer meadow birds like the black-tailed godwit (*Limosa limosa*) the required variation in sward herbage mass and development stage (Terwan and Guldemond, 2002).

3. The framework currently addresses hierarchical levels of field–farm–landscape, but can be applied to larger territories and higher hierarchical levels of for instance landscape–region–country. The compartmentation of the territory should then consist of larger land units such as landscapes and larger landscape structures of a few km^2, and nature of the production activities and design criteria should be adjusted (cf., Van Ittersum et al., 1998).

To evaluate the above mentioned issues 1. and 2., the Landscape IMAGES framework will be further developed in cooperation with stakeholders in the Northern Frisian Woodlands. The questions of stakeholders and available scientific knowledge and data form the basis for formulation of appropriate quantitative relations for the generation of production activities. These can be implemented in the integrating model for a specific case study area.

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